3. FASTER THAN LIGHT?

"Nonlocality gets more real". This is the provocative title of a bulletin in the December `98 issue of "Physics Today." It reports the completion of experiments performed at Innsbruck, Los Alamos, and Geneva that all confirm to high accuracy some predictions of quantum theory that appear to entail superluminal action at a distance.

The work done in Switzerland is the most spectacular of the three efforts. It got wide press coverage because it confirms the validity of this mysterious holistic quality of nature, not merely at the atomic scale of a billionth of a meter, nor even over a laboratory scale of meters, but now over a geographic scale of more than ten kilometers.

Many experiments of this general kind, but involving shorter distances, have been carried out over the past thirty years. The popular and technical accounts of these works invariably stress that they imply an interconnectedness of the physical universe that contradicts the simple conception of nature that ruled science from the time of Isaac Newton until the dawn of the twentieth century. However, those accounts never provide both a sufficient description of the experiment together with the detailed argumentation that demonstrates their action-at-a-distance implications, and hence the rational need to adopt new ideas about the nature of the world. These experiments do show conclusively that the old notions fail, and fail decisively far beyond the realm of atomic-scale distances.

Surely, no reasonable person should accept on hearsay a radical new idea of reality that overturns everything that has been believed for generations, and is, moreover, wildly counterintuitive: the physicists who are setting forth this "craziness" might be carried away by enthusiasm, or be so beguiled by the power of their mathematical tools that they lose touch with reality. This abrogation of the formerly well established science has such far-reaching consequences that any serious thinker needs to understand for himself the empirical evidence and its logical implications. Accordingly, I shall now describe in non-technical terms, first very schematically and later in more detail, the experiment performed in Switzerland by members of the Applied Physics Group of the University of Geneva, and then explain how their results contradict the classical-physics principle that bans faster-than-light action at a distance.

Very briefly, the overall general form of the Swiss experiment is this. First, a pair of highly correlated "twin-particles" is created by a special procedure performed in downtown Geneva. One of the two twins is sent to a laboratory in Bellevue, and the other is sent to a laboratory in Bernex. In each lab the arriving twin is sent into one or the other of two devices, which subjects it to one or the other of two alternative possible actions. The choice between these two alternative devices is made in a random fashion. Each twin is then examined in a way that produces one or the other of two alternative possible observable outcomes. The random choices made in the two far-apart regions, and the subsequent actions, are all performed so quickly that no information about which action is chosen in either lab has time to get to the other lab before the experiment there is completed---unless the information travels faster than light.

Classical physics forbids faster-than-light transfer of information. If that condition were satisfied then the behavior of neither twin could depend upon which of the two actions was randomly chosen and performed upon his faraway sibling. However, that condition of non-dependence cannot be reconciled with the predictions validated in this experiment.

Before expanding this cryptic synopsis of the experiment and its implications into a more generous offering it will be helpful to review the theoretical background.

According to Einstein's theory of relativity, any faster-than-light action would, from some point of view, be instantaneous. But instantaneous action at a distance is anathema to many scientists, on aesthetic and intuitive grounds. Of course, Newton's theory of gravity postulated an instantaneous action at a distance over a planetary scale, without any explanation of what was transmitting this action, and Newton's theory was severely criticized on that account. Even Newton himself was troubled by this feature. In a letter to his friend Bentley, he expressed his own skepticism about the notion of non-mediated action at a distance, and by implication, I think, about any instantaneous action at a distance:

",…that one body may act upon another at a distance
through a vacuum, without the mediation of anything else, by
and through which their action and force may be conveyed
from one to another, is to me so great an absurdity, that I
believe no man, who has in philosophical matters a
competent faculty of thinking, can ever fall into it. Gravity
must be caused by an agent acting constantly according to
certain laws, but whether this agent be material or immaterial
I have left to the consideration of my readers."

More than two centuries later Einstein's general theory of relativity explained gravity as being due to the warping of space-time by the presence of matter. According to this theory, the gravitational effect is indeed conveyed from point to point by a local-contact kind of interaction that transfers information no faster than the speed of light. Thus Einstein accomplished what Newton had intuited, the abolition of instantaneous action at a distance. He also enunciated the closely connected principle of no faster-than-light action. But this demand was imposed upon, and was directly relevant to, a conception of nature in which the continuous history of the physical world for all time was determined by certain simple immutable laws from the state of the world at early times.

When quantum theory was created Einstein objected forcefully to the "mysterious action at a distance", which is explicitly built into the normal computational procedures, and which, as we shall now see, directly infects also the predictions derived from those calculations.

The initial phase of the Swiss experiment occurs at a lab in downtown Geneva. That is where the twins are born. This birthing is achieved by directing a laser beam at a crystal. Most of the laser light goes through the crystal, but each laser photon in a small subset is split into a pair of photons, with each member of the pair carrying about half the energy of its laser-photon parent.

For some of these pairs one partner is sent by optical fiber to a lab in the village of Bellevue, while the other partner is sent to a lab in the town of Bernex. These two labs lie more than ten kilometers apart.

At each lab the arriving twin is sent into an "interferometer".

Interferometers are, themselves, very interesting devices, and they need to be understood if the experiment is to be made clear.

These instruments exhibit in a striking way one essential aspect of the quantum mystery: wave-particle duality. What they reveal is similar in principle to what is shown by the famous double-slit experiment. But the double-slit experiment involves many detectors of photons and many possible trajectories that they might traverse. Only two detectors and two paths are needed for an interferometer, and the whole situation is consequently much clearer.

There are different kinds of interferometers. For ease of explanation I shall describe one that is slightly different from what was used in the Swiss experiment. But the principle is the same.

This interferometer involves two ordinary (i.e., fully silvered) mirrors, each of which reflects all the light falling on it, and two half-silvered mirrors, each of which reflects (like a mirror) half the light incident upon it, and transmits (like a plate of clear glass) the other half.

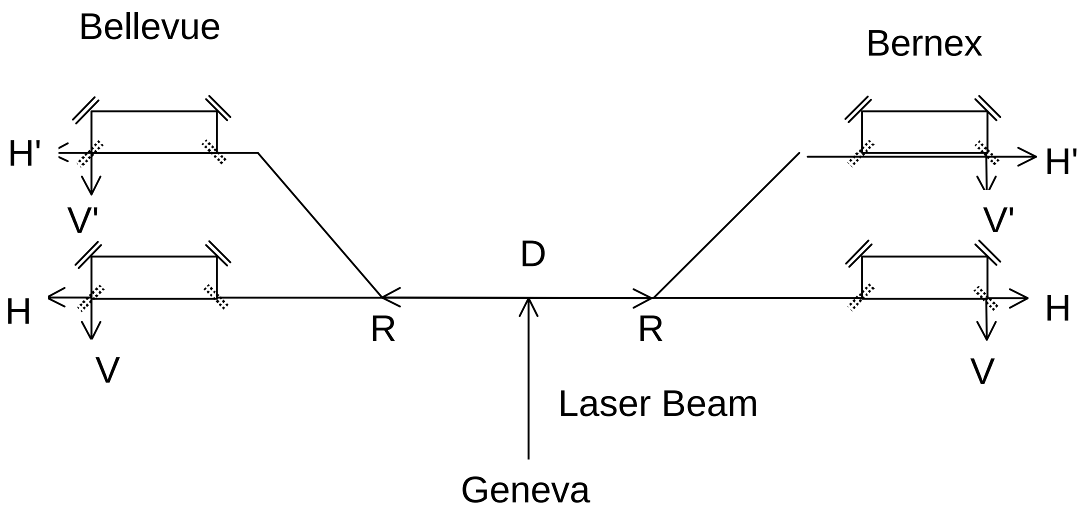
Suppose the beam entering one of these devices is traveling horizontally. Upon entering the interferometer this beam strikes a half-silvered mirror that is slanted at 45 degrees. Half the light goes straight though, while the other half is deflected vertically upwards. The half that goes straight through travels a short distance and then strikes the second half-silvered mirror, which is cocked at 45 degrees in the opposite direction, so that half of that beam goes straight through, and exits the device horizontally, whereas the other half is deflected vertically downward, and exits vertically.

A photon detector is placed in each of these two exit beams. Let the detector placed in the horizontal exit beam be called the horizontal-beam detector H, and the photon detector placed in the vertical exit beam be called the vertical-beam detector V.

The half-beam that was deflected vertically upward at the first half-silvered mirror takes a round-about path, via the two fully silvered mirrors, to the second half-silvered mirror: it is reflected by the first of these two mirrors into a horizontal beam that runs parallel to the original horizontal beam, and is then reflected back downward to the second half-silvered mirror. Thus half of the original beam travels a short route between the two half-silvered mirrors along the bottom side of a rectangle whereas the other half takes a longer path along the other three sides.

At the second half-silvered mirror both halves of the beam, the one traveling the shorter direct route, and the one taking the longer round-about route, both split 50-50, with half going out along the horizontal exit beam and the other half exiting along the (downward-directed) vertical exit beam.

Because there are two interferometers in each village, and each one has two photon detectors, there are four detectors in each village, and hence eight altogether. But for each particle pair the two independent random processes will select only one or the other of the two interferometers in each village.



The Experimental Set up.

[The laser beam is split at D. The two R's indicate the two random processes, each of which randomly sends the photon that arrives in its laboratory to one or the other of the two interferometers. H and V label the photon detectors in the horizontal and vertical exit channels, respectively. The primes indicated alternative possibilities.]

Some of the photons get lost along the way and do not reach a detector. But there are many pairs whose two members both reach detectors, one in Bellevue, the other in Bernex. Signals from those two detectors are sent back by ordinary wires to a central processor in Geneva.

[There is one fine point, which needs mention, but which is not central to the main argument.

The prediction of quantum theory that we want to use concerns the subset of pairs such that both members, one in Bellevue the other in Bernex, take the long path or both take the short path. To distinguish these pairs from the others, the lengths of the various paths are adjusted so that, on a nanosecond time scale, the *difference* between the times it takes light to traverse the two long paths, one in each village, is equal to the *difference* between the times it takes light to traverse the two short paths. Consequently, the *difference* in the arrival times of the two paired pulses, one from each of the two villages, is independent of whether both of the paired photons take the long path in their respective villages or both take the short path. This time difference is measured by fast (nanosecond) electronics. The paired pulses coming from paired photons that both take the long path or both take the short path will have the *same time difference*, but the pairs such that one partner takes a long path and the other takes a short path will *have different time differences.*This effect can be used to identify, and cast aside, the pairs such that the member in one village takes a short path and its partner in the other village takes the long path. Retained are those pairs in which both of the twins (one in each village) take the longer path or both take the shorter path. This sample is singled out and analyzed because quantum theory predicts that for the photon pairs in this subset a strong and interesting correlation exists between what happens in the two villages.

The rate at which the pairs are detected is slow enough so that each pair of particles, one detected in Bellevue the other in Bernex, can be distinguished from all the other pairs by fast electronics. A pair is classified as "matched" if both members are detected in a horizontal exit channel or both are detected in a vertical channel. They are "unmatched" if one partner is detected in a horizontal exit channel and its mate is detected in a vertical exit channel.

Quantum theory predicts that the fraction of the pairs that are unmatched will depend on L minus S, where L is the *sum* of the two long paths, one in each village, and S is the *sum* of the two short paths. For certain values of L minus S all of the pairs will be unmatched and for other values of L minus S none of the pairs will be unmatched. For intermediate values of L minus S a certain fraction f will be unmatched.

Quantum theory gives a precise formula for this fraction f, and the validity of this formula, for many values of L minus S, was checked by the Swiss experiment. For ease of explanation, I shall use just one simple property of this formula: if for some original value of L minus S none of the pairs are unmatched then for small shifts of L minus S away from this original value the number of unmatched pairs will grow like the *square* of this small shift. In particular, the fraction f of unmatched pairs will increase *faster than linearly,* relative to the change in L minus S!

What is so astonishing about that?

What is puzzling and interesting is this: *This faster-than-linear growth is impossible to reconcile with the classical idea that the choice of what is done to a twin cannot influence the behavior of its sibling---before the information about which action performed on the one partner can reach the other, without traveling faster than light.*

How is this remarkable result proved?

In the actual experimental situation the four alternative kinds of settings come in some random sequence, and the experimenters collect together the experiments with the four alternative combination of settings, in order to check, for each of the four different values of L minus S, that the fraction of unmatched pairs is what quantum theory predicts.

However, within the context of classical physics one has an underlying theoretical structure that allows one to consider a set of four theoretically possible worlds that are identical up until the instant at which the two random process act. The random processes are supposed to be independent of the system being examined: cosmic rays, or any one of a billion different arbitrary processes could control them. One implements this idea in classical physics (and also in quantum physics) by fixing in slightly different ways the external potential energy in which the system being examined moves. This external potential is set in a way such that a tiny change triggers the choice between the two alternative possible experiments in Bellevue. A second independent potential energy variation is invoked to implement the random choice made in Bernex.

Relativistic classical physics is designed so that every physical effect of one of these tiny alterations of the potential is confined to the region of space-time that can be reached by traveling no faster that light from the region of that tiny change. This is how the idea of no-faster-than-light influences is made precise in physics.

The random process in Bellevue directs the photon arriving at Bellevue either into the interferometer BL or into the interferometer BL'. And the random process in Bernex directs the photon arriving in Bernex into either BR or BR'. The subsequent evolution of each of the four alternative possible worlds will continue to be identical to each other, except for the dynamical consequences of these two localized random choices. In classical physics these consequences propagate no faster than the speed of light. Hence under the conditions of the Swiss experiment a change in the random choice made in either region can have no effect at all in the other region until after the detection is made and recorded there. (Recall that the experiment is designed so that the random choice in each region is followed so quickly by the detection and recording there that no effect of the faraway choice upon these two latter processes is possible without superluminal action.)

To deduce a contradiction between this no-faster-than-light condition and the predictions validated by the Swiss experiment consider the following arrangement. Let the first alternative interferometers BL and BR in Bellevue and Bernex, respectively, be copies of each other, and let BL' and BR' be copies of each other. Let the short paths in BL, BR, BL' and BR' all have the same lengths. But let the longer path in BL' (hence also in BR') be slightly longer than the longer path in BL (hence also in BR). (This difference is negligible on the nanosecond time scale mentioned earlier.) Let the path lengths in BL (and hence in BR) be fixed so that in the case that BL and BR are chosen by the random processes there will be no "unmatched" pairs: i.e., there will be no pairs such that the twin in one village is detected in a horizontal exit channel and the twin in the other village is detected in the vertical exit channel. This original case will be called Case One.

Case Two is the alternative possible world in which everything is the same as in Case One up until the moment that the two random choices were made, but in which the random choice in Bellevue goes the other way, and BL' is picked by the random process there, rather than BL, but nothing is changed in Bernex. Now a small fraction f of the pairs will be "unmatched". Since nothing has changed in Bernex, this small fraction f of unmatched events must arise from a switching of this fraction f of the events in Bellevue from what they were in Case One. That is, if in a sequence of, say, ten thousand original pairs the sequence of detection events is, say (H, V, V, H, H, H, V, H, etc.) in both Bellevue and Bernex (I shall ignore statistical fluctuations, which do not materially affect the argument) then the fraction f, say 1%, of these values will in Case Two be reversed from their Case One values in Bellevue, but none will be reversed in Bernex. This is the first key consequence of the no-faster-than-light-influence condition: it ensures that the change made in Bellevue does not disturb the outcomes in Bernex.

Case Three is the same as Case One in Bellevue, but BR' is chosen in Bernex instead of BR. Hence the same fraction f of the detection events, but now in Bernex, must be opposite to what they were in Case One.

In case Four Case the changes from Case One that were made in Bellevue alone in Case Two, and in Bernex alone in Case Three, are now made simultaneously in both Bellevue and Bernex. Hence in this final case, Case Four, the changes that occur in Bellevue must be the same as the changes made there in Case Two, since no influence of the choice made in Bernex can be present in Bellevue. Similarly, in this Case Four, the changes made in Bernex must be the same as the changes that were made there in Case Three. But then the total number of mismatches in Case Four can be no greater than the sum of the number of mismatches in Cases Two and Case Three. Thus the fraction f* of mismatches in Case Four can be no larger than 2f. (Of course, there can be fluctuations, but by taking the numbers of pairs considered to be very large the fluctuations become unimportant.).

On the other hand, in Case Four the empirically validated theoretical formula for this fraction f* is, for small f, proportional to the *square* of the shift in L minus S from its value in Case One. This shift is the *sum* of these shifts in L minus S for Case Two and Case Three separately, because L and S are both just sums over the contributions from Bellevue and Bernex individually. Thus this shift in L minus S is *twice* what it was for Case Two. But this value must be *squared* to give the empirically validated formula, and 2 squared is 4! Thus theory, and the empirical evidence, say that the fraction of unmatched pair in this Case Four is close to 4f, whereas the no-faster-than-light condition allows it to be no greater than 2f.

This means that both quantum theory and nature are incompatible with the classical notion that what is done to one twin cannot affect the behavior of its faraway mate---faster than the speed of light!

In this particular proof the effect is small when f is small. But in other arrangements the effect can be that locality requires a fraction to vanish that quantum theory predicts to be, say, 99%. In any case, it is the principle that counts not the numerical particulars. And the principle established by this analysis is that *the causality concepts of classical physics fail over macroscopic distances.*